

CP VIOLATION IN HYPERON DECAYS*

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Abstract

The present status for CP violation in hyperon decays is reviewed.

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I. INTRODUCTION

Non-leptonic hyperon decays of Λ , Σ and Ξ [1–8] are interesting processes to test CP conservation outside the neutral Kaon system. Measurements of CP violation in hyperon decays will provide us with useful information about the origin of CP violation. Several proposals have been made to look for CP violation in hyperon decays [6,7]. Recently the E871 proposal at Fermilab has been approved [8]. The expected sensitivity for CP violation test is about the same order of magnitude as the Standard Model (SM) prediction. This experiment will measure CP violation in $\Xi^- \rightarrow \Lambda\pi^-$ and $\Lambda \rightarrow p\pi^-$. The E871 experiment will start to take data as early as 1996. In this talk we will review the present status for CP violation in hyperon decays. We will concentrate on Ξ and Λ decays because there is not hope to measure CP violation in Σ decays in the near future.

Non-leptonic hyperon decays can proceed into both S-wave and P-wave final states with amplitudes S and P, respectively. One can write the amplitude as

$$Amp(B_i \rightarrow B_f \pi) = S + P \vec{\sigma} \cdot \vec{q}, \quad (1)$$

where \vec{q} is the momentum of the final baryon B_f . Experimental observables are: the decay width Γ , and the parameters in the decay angular distribution. In the rest frame of the initial hyperon, the angular distribution is given by

$$\frac{4\pi}{\Gamma} \frac{d\Gamma}{d\Omega} = 1 + \alpha \hat{s}_i \cdot \hat{q} + \hat{s}_f \cdot [(\alpha + \hat{s}_i \cdot \hat{q})\hat{q} + \beta \hat{s}_i \times \hat{q} + \gamma(\hat{q} \times (\hat{s}_i \times \hat{q}))], \quad (2)$$

where $s_{i,f}$ are the spins of the initial and final baryons, respectively. \hat{v} indicates the direction of the corresponding vector. The parameters α , β and γ are defined as

$$\alpha = \frac{2Re(S^*P)}{|S|^2 + |P|^2}, \quad \beta = \frac{2Im(S^*P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}. \quad (3)$$

Only two of them are independent. We will discuss α and β . In the literature, β is sometimes parametrized as $\beta = \sqrt{1 - \alpha^2} \sin\phi$.

It is convenient to write the amplitudes as

$$S = \sum_i S_i e^{i(\phi_i^S + \delta_i^S)} , \quad P = \sum_i P_i e^{i(\phi_i^P + \delta_i^P)} \quad (4)$$

to explicitly separate the strong rescattering phases δ_i and the weak CP violating phases ϕ_i .

The decay amplitudes \bar{S} and \bar{P} for anti-hyperon can be parametrized in a similar way.

Then

$$\bar{S} = - \sum_i S_i e^{i(-\phi_i^S + \delta_i^S)} , \quad \bar{P} = \sum_i P_i e^{i(-\phi_i^P + \delta_i^P)} . \quad (5)$$

We will denote the observables in anti-hyperon decays with a bar on the corresponding ones in hyperon decays.

II. CP VIOLATING OBSERVABLES

Several CP violating observables can be constructed using the observables discussed in the previous section. The interesting ones are [2]

$$\begin{aligned} \Delta &= \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} , \quad A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}} \approx \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} + \Delta , \\ B &= \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}} \approx \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}} + \Delta . \end{aligned} \quad (6)$$

All these CP violating observables can, in principle, be measured experimentally. It has been shown that the low energy reaction $p_i \bar{p}_i \rightarrow \Lambda \bar{\Lambda} \rightarrow p_f \pi^- \bar{p}_f \pi^+$ can be used to measure A for Λ [9]. The measurement

$$\tilde{A} = \frac{N_p^+ - N_p^- + N_{\bar{p}}^+ - N_{\bar{p}}^-}{N_{total}} , \quad (7)$$

is equal to $P_A \alpha_A A(\Lambda)$. Here N_p^\pm indicates events with $(\hat{p}_i \times \hat{P}_\Lambda) \cdot \hat{p}_f > 0$ or < 0 , and similarly for anti-particles. P_A is the polarization of the Λ produced in the $p\bar{p}$ collision.

The measurement of B requires the analysis of the polarization of the final baryon. Low energy $p\bar{p}$ collision can also measure B for Ξ decays [9]. In the process, $p_i \bar{p}_i \rightarrow \Xi \bar{\Xi} \rightarrow \Lambda \pi^- \bar{\Lambda} \pi^+ \rightarrow p_f \pi^- \pi^- \bar{p}_f \pi^+ \pi^+$, one can measure

$$\tilde{B} = \frac{\tilde{N}_p^+ - \tilde{N}_p^- + \tilde{N}_{\bar{p}}^+ - \tilde{N}_{\bar{p}}^-}{N_{total}} , \quad (8)$$

where \tilde{N}_p^\pm indicates events with $\hat{P}_\Xi \cdot (\hat{p}_f \times \hat{p}_\Lambda) > 0$ or < 0 , and similarly for anti-particles. \tilde{B} is given by $(\pi/8)P_\Xi\alpha_\Lambda\beta_\Xi(A(\Lambda) + B(\Xi))$, and hence a measurement of \tilde{A} and \tilde{B} yields $A(\Lambda)$ and $B(\Xi)$.

There have been some measurements for CP violation in hyperon decays by several groups,

$$\begin{aligned}
A(\Lambda \rightarrow p\pi^-) &= -0.02 \pm 0.14, \quad \text{From } p\bar{p} \rightarrow \Lambda X \text{ and } p\bar{p} \rightarrow \bar{\Lambda} X. \quad \text{Ref. [10]} \\
A(\Lambda \rightarrow p\pi^-) &= -0.07 \pm 0.09, \quad \text{From } p\bar{p} \rightarrow \Lambda\bar{\Lambda} \rightarrow p\pi^- \bar{p}\pi^+. \quad \text{Ref. [11]} \\
A(\Lambda \rightarrow p\pi^-) &= 0.01 \pm 0.10, \quad \text{From } J/\psi \rightarrow \Lambda\bar{\Lambda} \rightarrow p\pi^- \bar{p}\pi^+. \quad \text{Ref. [12]}
\end{aligned} \tag{9}$$

The experiment at E871 will measure $\alpha_\Lambda\alpha_\Xi$ in the decay $\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^-\pi^-$, and similar measurement for anti- Ξ decays [8]. An asymmetry A_{asy} can be extracted

$$A_{asy} = \frac{\alpha_\Lambda\alpha_\Xi - \bar{\alpha}_\Lambda\bar{\alpha}_\Xi}{\alpha_\Lambda\alpha_\Xi + \bar{\alpha}_\Lambda\bar{\alpha}_\Xi} \approx A(\Lambda) + A(\Xi). \tag{10}$$

The expected sensitivity for A_{asy} is 10^{-4} and may reach 10^{-5} which would test the SM predictions.

III. THEORETICAL CALCULATIONS

There are large uncertainties in theoretical calculations for the CP violating observables due to our poor understanding of the hadronic matrix elements. To reduce errors it is best to use experimental measurements for CP conserving quantities and to calculate CP violating parameters theoretically, that is, we calculate the weak phases $\phi^{s,p}$. The experimental data on CP conserving quantities are summarized below.

The isospin decomposition of Λ and Ξ are given by [13]

$$\begin{aligned}
\Lambda \rightarrow p\pi^- , \quad S(\Lambda_-^0) &= -\sqrt{\frac{2}{3}}S_{11}e^{i(\delta_1+\phi_1^s)} + \sqrt{\frac{1}{3}}S_{33}e^{i(\delta_3+\phi_3^s)} , \\
P(\Lambda_-^0) &= -\sqrt{\frac{2}{3}}P_{11}e^{i(\delta_{11}+\phi_1^p)} + \sqrt{\frac{1}{3}}P_{33}e^{i(\delta_{33}+\phi_3^p)} ,
\end{aligned}$$

$$\begin{aligned}
\Lambda \rightarrow n\pi^0, \quad S(\Lambda_0^0) &= \sqrt{\frac{1}{3}}S_{11}e^{i(\delta_1+\phi_1^s)} + \sqrt{\frac{2}{3}}S_{33}e^{i(\delta_3+\phi_3^s)}, \\
P(\Lambda_0^0) &= \sqrt{\frac{1}{3}}P_{11}e^{i(\delta_{11}+\phi_1^p)} + \sqrt{\frac{2}{3}}P_{33}e^{i(\delta_{33}+\phi_3^p)}, \\
\Xi^- \rightarrow \Lambda\pi^-, \quad S(\Xi_-^-) &= S_{12}e^{i(\delta_2+\phi_{12}^s)} + \frac{1}{2}S_{32}e^{i(\delta_2+\phi_{32}^s)}, \\
P(\Xi_-^-) &= P_{12}e^{i(\delta_{21}+\phi_{12}^p)} + \frac{1}{2}P_{32}e^{i(\delta_{21}+\phi_{32}^p)}, \\
\Xi^0 \rightarrow \Lambda\pi^0, \quad S(\Xi_-^-) &= \sqrt{\frac{1}{2}}(S_{12}e^{i(\delta_2+\phi_{12}^s)} - S_{32}e^{i(\delta_2+\phi_{32}^s)}), \\
P(\Xi_-^-) &= \sqrt{\frac{1}{2}}(P_{12}e^{i(\delta_{21}+\phi_{12}^p)} - P_{32}e^{i(\delta_{21}+\phi_{32}^p)}). \tag{11}
\end{aligned}$$

These decays are dominated by the $\Delta I = 1/2$ amplitudes. Experimental measurements give: [14] $S_{33}/S_{11} = 0.027 \pm 0.008$, $P_{33}/P_{11} = 0.03 \pm 0.037$; $S_{32}/S_{12} = -0.046 \pm 0.014$, and $P_{32}/P_{12} = -0.01 \pm 0.04$. From $N\pi$ scattering, the strong rescattering phase for Λ decays are determined to be [15]: $\delta_1 \approx 6.0^\circ$, $\delta_3 \approx -3.8^\circ$, $\delta_{11} \approx -1.1^\circ$ and $\delta_{31} = -0.7^\circ$ with errors of order 1° . The strong rescattering phases for Ξ decays are not experimentally determined. Theoretical predictions vary a large range. Nath and Kumer [16] obtained: $\delta_{21} = -2.7^\circ$ and $\delta_2 = -18.7^\circ$. Martin [17] obtained $\delta_{21} = -1.2^\circ$. Recently, Lu, Savage and Wise [18], using chiral perturbation theory, obtained $\delta_{21} = -1.7^\circ$ and $\delta_2 = 0$ to the lowest order. In this last estimate, contributions from $1/2^-$ and $3/2^-$ states are not included, which can give rise to a significant δ_2 .

To a very good approximation, the CP violating observables can be simplified to yield [2],

$$\begin{aligned}
\Delta(\Lambda_-^0) &= -2\Delta(\Lambda_0^0) = \sqrt{2}\frac{S_{33}}{S_{11}}\sin(\delta_3 - \delta_1)\sin(\phi_3^s - \phi_1^s), \\
A(\Lambda_-^0) &= A(\Lambda_0^0) = -\tan(\delta_{11} - \delta_1)\sin(\phi_1^p - \phi_1^s), \\
B(\Lambda_-^0) &= B(\Lambda_0^0) = \cot(\delta_{11} - \delta_1)\sin(\phi_1^p - \phi_1^s), \\
\Delta(\Xi_-^-) &= \Delta(\Xi_0^0) = 0, \\
A(\Xi_-^-) &= A(\Xi_0^0) = -\tan(\delta_{21} - \delta_2)\sin(\phi_{12}^p - \phi_{12}^s), \\
B(\Xi_-^-) &= B(\Xi_0^0) = \cot(\delta_{21} - \delta_2)\sin(\phi_{12}^p - \phi_{12}^s). \tag{12}
\end{aligned}$$

It is well known that for large top quark mass, there is considerable cancellation for the $I = 0$ and $I = 1$ contributions to ϵ'/ϵ , and ϵ'/ϵ can be quite small [19]. Such cancellation does not happen to the quantities A and B because they are dominated by $I = 1/2$ quantities. Hence hyperon decays probe a somewhat different operators, even in the SM, from ϵ'/ϵ .

A. The Standard Model Predictions.

In the SM, the origin of CP violation is the non-trivial phase in the KM matrix [20]. The effective Hamiltonian responsible for non-leptonic hyperon decays is given by

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{us} \sum_i C_i(\mu) Q_i, \quad (13)$$

where the sum is over all the Q_i four-quark operators, and the $C_i(\mu)$ is the Wilson coefficients. C_i contains both the CP conserving and CP violating parts. To separate KM mixings and other dependences, C_i is usually parametrized as $C_i = z_i + \tau y_i$, where $\tau = -V_{td}^* V_{ts} / V_{ud}^* V_{us}$. CP violating part is proportional to $Im(\tau)$. To obtain the weak phases, we need to evaluate

$$ImM = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{us} Im(\tau) < \pi B_f | \sum_i y_i(\mu) Q_i(\mu) | B_i >. \quad (14)$$

The quantity $y_i(\mu)$ is calculated by taking $y(m_W)$ as an initial value and then using renormalization group equation to reach the scale μ [19]. The most difficult part of the calculation is to evaluate $< \pi B_f | Q_i | B_i >$. At present, there is no convincing method to calculate these matrix elements. There are many models which can give estimates. However, it is known that all these models can not satisfactorily explain the $I = 1/2$ dominance in hyperon decays. They can at most produce the experimental amplitudes up to a factor of 2. It is therefore expected that the estimate for CP violation in hyperon decays can easily off by a factor of 2. The following is the result obtained by using the vacuum saturation and factorization approximation [4],

$$ImM = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{us} Im(\tau) [(M_1^s + M_3^s) V + (M_1^p + M_3^p) P], \quad (15)$$

with

$$\begin{aligned}
M_1^s &= \frac{y_1 - 2y_2}{3} - \frac{y_7}{2} + \xi \left(\frac{-2y_1 + y_2}{3} - y_3 - \frac{y_8}{2} \right) - Y \left(y_6 + \frac{y_8}{2} + \xi \left(y_5 + \frac{y_7}{2} \right) \right), \\
M_1^p &= \frac{y_1 - 2y_2}{3} - \frac{y_7}{2} + \xi \left(\frac{-2y_1 + y_2}{3} - y_3 - \frac{y_8}{2} \right) + Z \left(y_6 + \frac{y_8}{2} + \xi \left(y_5 + \frac{y_7}{2} \right) \right), \\
M_3^s &= -\frac{y_1 + y_2}{3} (1 + \xi) + \frac{y_7}{2} + \frac{y_8}{2} - Y (\xi y_7 + y_8), \\
M_3^p &= -\frac{y_1 + y_2}{3} (1 + \xi) + \frac{y_7}{2} + \frac{y_8}{2} + Z (\xi y_7 + y_8),
\end{aligned} \tag{16}$$

where $Y = 2m_\pi^2/(m_u + m_d)(m_s - m_u)$, $Z = 2m_\pi^2/(m_u + m_d)(m_s + m_u)$, and $\xi = 1/N$ with N the number of color.

For $\Lambda \rightarrow p\pi^-$,

$$V = i\sqrt{2}F_\pi(m_\Lambda - m_p)\sqrt{\frac{3}{2}}\bar{p}\Lambda, \quad P \approx -i\frac{2F_\pi F_K m_\pi^2}{m_K^2 - m_\pi^2} g_{\Lambda p K} \bar{p} \gamma_5 \Lambda, \tag{17}$$

where m_i are the masses of the particle i , $F_\pi = 93$ MeV, $F_K \approx 1.3F_\pi$ and $g_{\Lambda p K} \approx -13.3$. Similarly one can obtain the decay amplitudes for Ξ decays.

Using these estimates for the matrix elements and information for the CP violating parameter $Im(\tau)$ from ϵ and other constraints [4], predictions for the CP violating observables Δ , A and B can be obtained. Δ is predicted to be less than 10^{-6} . It is very small. The parameter $A(\Lambda)$ is in the range $-(0.5 \sim 0.1) \times 10^{-4}$. $B(\Lambda)$ is about 60 times larger.

The same calculation has been done using MIT bag model [2] and other models for hadronic matrix elements [3,4]. The MIT bag model predicts the same orders of magnitude for A and B as the vacuum saturation predictions. Larger values are possible in other models [4]. It has recently been shown that the gluon dipole operator also has significant contributions to $A(\Xi)$ [5]. In Table 1, We list the allowed ranges of Δ , A and B using MIT bag model for Λ and Ξ decays. The ranges include uncertainties from the KM matrix elements and uncertainties in top quark mass [4]. In particular, $A(\Xi)$ is in the range $-(0.1 \sim 1) \times 10^{-4}$ and hence the quantity A_{asy} to be measured by E871, $A(\Lambda) + A(\Xi)$, is expected to be in the range $-(0.2 \sim 1.5) \times 10^{-4}$.

B. The Multi-Higgs Model Predictions.

I will consider multi-Higgs model with neutral flavour current conservation at the tree level and CP is violated spontaneously. This is the model proposed by Weinberg [21]. In this model the most important operator related to CP violation is

$$L_{CPV} = i\tilde{f}\bar{d}T^a\sigma_{\mu\nu}(1 - \gamma_5)sG_a^{\mu\nu} , \quad (18)$$

where $G_a^{\mu\nu}$ is the gluon field strength, T^a is the $SU(3)_C$ generator, and \tilde{f} is a constant depending on several parameters. This operator can reproduce CP violation in the neutral Kaon sector provided that [22]

$$m_K\sqrt{2}|\epsilon|\Delta m_{K_L-K_S} \approx 10^{-7} < \pi^0|L_{CPV}|K^0 > . \quad (19)$$

This fixes the strength of CP violation in this model. The predictions for CP violation in hyperon decays have been carried out in Ref.[2] using bag model and pole model calculations. The results are listed in Table 1.

In models in which flavor changing neutral currents are responsible for CP non-conservation, all effect in hyperon decays as well as ϵ'/ϵ are essentially zero.

C. The Left-Right Symmetric Model Predictions.

The Left-Right symmetric models are based on the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. In this model there are additional CP violating phases from the right-handed KM matrix. Here we consider a simple model of this type, the "isoconjugate" Left-Right model [23]. In this model there is no mixing between W_L and W_R . There is no CP violation in the left-handed sector. All CP violations are coming from the right-handed KM matrix. And $|V_{Lij}| = |V_{Rij}|$ for the KM matrices. The full $\Delta S = 1$ Hamiltonian has the form

$$H_W = \frac{G_F}{\sqrt{2}}(O_{LL} + \eta e^{i\beta}O_{RR}) . \quad (20)$$

The operators O_{LL} and O_{RR} are identical operators, except that O_{LL} is a product of two left-handed currents whrease O_{RR} has two right-handed currents. Because this structure, one can easily see that parity-nonconserving processes have an identical phase factor $1 + i\eta\beta$, while all parity-conserving ones have phase $1 - i\eta\beta$. We have: $\phi_i^s = \eta\beta$ and $\phi_i^p = -\eta\beta$ for all decays. The strength is fixed by requiring this phase to explain CP violation in the neutral Kaon system [24]. From this consideration, $\eta\beta$ is determined to be about 4.4×10^{-5} . Because the simple phase structure, Δ is always zero in this model. The predictions for A and B are given in Table 1.

Table 1. Predictions of CP violation in hyperon decays.

Λ decay	KM model	Weinberg Model	Left-Right Model
$\Delta(\Lambda_-^0)$	$< 10^{-6}$	-0.8×10^{-5}	0
$A(\Lambda_-^0)$	$-(5 \sim 1) \times 10^{-5}$	-2.5×10^{-5}	-1.1×10^{-5}
$B(\Lambda_-^0)$	$(3 \sim 0.6) \times 10^{-4}$	1.6×10^{-3}	7.0×10^{-4}
Ξ decay			
$\Delta(\Xi_-)$	0	0	0
$A(\Xi_-)$	$-(10 \sim 1) \times 10^{-5}$	-3.2×10^{-4}	2.5×10^{-5}
$B(\Xi_-)$	$(10 \sim 1) \times 10^{-3}$	3.8×10^{-3}	-3.1×10^{-4}

From Table 1 we see that, in general, Δ is very small. It may be difficult to measure it experimentally. The prediction for the CP violating observable A is close to the region which will be probed by the E871 experiment, with experimental sensitivity 10^{-4} to 10^{-5} in A_{asy} , new and useful information about CP violation will be obtained.

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